26 July 2006
AIAA
S-120-200X

Standard

Mass Properties Control for Space Systems

DRAFT

Warning
This document is not an approved AIAA Standard. It is distributed for review and comment. It is subject to change without notice.
Recipients of this draft are invited to submit, with their comments, notification of any relevant patent rights of which they are aware and to provide supporting documentation.

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

XX Month 2006

Abstract

This standard defines terminology and establishes uniform processes, procedures, and systematic methods for the management, control, monitoring, determination, verification, and documentation of the mass properties during the design and development phases of space systems, including their components and subsystems. This standard applies to space vehicles (SV), upper stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles (LV), and ballistic vehicles.

DRAFT

LIBRARY OF CONGRESS CATALOGING DATA WILL BE ADDED HERE BY AIAA STAFF

Published by
American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Reston, VA 20191

Copyright © 2006 American Institute of Aeronautics and Astronautics
All rights reserved

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without prior written permission of the publisher.

Printed in the United States of America

Contents

Foreword v
1 Scope 1
2 Tailoring 1
3 Applicable Documents 1
4 Vocabulary 1
4.1 Acronyms and Abbreviated Terms 1
4.2 Terms and Definitions 2
5 Requirements 5
5.1 Mass Properties Control 5
5.1.1 Scope 5
5.1.2 Mass Properties Control Plan 5
5.1.3 Mass Properties Control Process 6
5.2 Analysis Plan 14
5.2.1 Scope 14
5.2.2 Methods of Analysis 15
5.2.3 Analysis Parameter Requirements and Recording of Analysis 15
5.2.4 Flight Hardware Analysis 16
5.2.5 Special Analyses 17
5.2.6 Ground Operations Support Analysis 19
5.2.7 Post Flight Analysis 19
5.2.8 Breakup Analysis/Disposal 19
5.3 Verification 19
5.3.1 Verification Plan 19
5.3.2 Test Plan 20
5.3.3 Standard Work Instruction (SWI) 22
5.3.4 Test Procedure (TP) 22
5.4 Database Management 24
5.4.1 Scope 24
5.4.2 Data Management System 25
5.4.3 Data Organization Utility 25
5.4.4 Database Record Keeping 26
5.5 Documentation 26
5.5.1 Documentation Requirements 26
5.5.2 Document Elements 27
5.5.3 Document Element Description 27

DRAFT

Annex A Supplemental Information for Terms and Definitions (Informative) 33
A.1 Mathematical Descriptions 33
A.2 Vehicle Specific Mass Definitions 34
Annex B Placeholder heading (info moved to Section 5.2.4.3) 35
Annex C Functional Breakdown of Mass (Informative) 36
C.1 Scope 36
C.2 Referenced Documents 36
C.3 Approach 36
Annex D Space System Design Features (Informative) 44
D.1 Scope 44
D.2 Referenced Documents 44
D.3 Major Reporting Parameters 44
Annex E Document Content and Submittal Schedule (Normative) 47
E.1 Schedule of Submittals 47
E.2 Distribution 47
Bibliography 50

Figures

Figure 1 — General Mass Definitions 5
Figure 2 — Sample Plot of Mass Versus Time 11
Figure 3 — Example Mass Properties Control Process 10

Tables

Table 1 — Mass Growth Allowance and Depletion Schedule 1
Table 2 — Example TPM Chart for Mass 10
Table 3 — Mass Change Codes and Definitions 17
Table C.1 — Sample Functional Breakdown (Satellite) 38
Table C.2 — Sample Functional Breakdown (Liquid Propulsion Stage) 39
Table C.3 — Sample Functional Breakdown (Non-Man Rated Launch/Ballistic Vehicles) 41
Table C.4 — Sample Functional Breakdown (Manned Reentry Vehicle) 42
Table C.5 — Category Descriptions 43
Table E.1 — Example Document Content and Submittal Schedule 48
Table E.2 — Example Document Content and Submittal Schedule 49

DRAFT

Foreword

This document is intended as a guide for mass properties control plans. This information may also be used for requirements during preparation of acquisition contract and program specific documents.

This standard combines MIL-STD-1811, MIL-HDBK-1811 Handbook for Mass Properties Control for Space systems, and MIL-M-38310B Mass Properties Control Requirements for Missile and Space systems. This standard implements proven methods and lessons learned for effective mass properties control and combines tools necessary for timely evaluation of program mass properties, and it enables early decision making regarding possible design changes in program direction.

The primary objectives of this document are to provide effective and uniform processes for space system mass properties control, analysis, verification, data management, and documentation. It is intended to be as comprehensive as practical and will be periodically updated to incorporate advances and innovations.

At the time of approval, the members of the AIAA Mass Properties Committee on Standards were:

Tom Ajluni	Swales Aerospace
Pete Baldwin	Lockheed Martin Space Systems Company
Kevin Bee	ATK Thiokol
Geoffrey Beech	NASA MSFC
Roger Belt, Co-Chair	The Boeing Company
Uno Carlsson	Orbital Sciences Corporation
Gerard Drewek	General Dynamics-Advanced Information Systems
David Finkleman	Center for Space Standards and Innovation
Michael Froehlich	Ball Aerospace & Technologies Corporation
William Griffiths	The Aerospace Corporation
Mahantesh Hiremath	Stellar Solutions, Inc.
Gary Holloway	Lockheed Martin Space Systems Company
Roland Holzmann	The Boeing Company
Quang Lam	Orbital Sciences Corporation
Bell Lee	Raytheon
Dean Liensdorf	Lockheed Martin Space Systems Company
Ian MacNeil	The Boeing Company
Andrew McGill	The Boeing Company
Thomas McGovern	Lockheed Martin Corporation
Hans Naepflin	Raytheon
John Nakai	Northrop Grumman
Geoffrey Reber	The Aerospace Corporation
Glen Richbourg	Lockheed Martin Space Systems Company

DRAFT

Ric Roy	The Boeing Company
Phillip Slattery	Space Systems/Loral
Ronald Solomon	Northrop Grumman
Richard Sugiyama	The Aerospace Corporation
Joseph Vecera	Honeywell
Ernest Wade	The Aerospace Corporation
Louis Yang, Co-Chair	The Aerospace Corporation
Robert Zimmerman	Lockheed Martin Corporation

The above consensus body approved this document in Month 200X.

The AIAA Standards Executive Council (VP-Standards Name, Chairman) accepted the document for publication in Month 200X.

The AIAA Standards Procedures dictate that all approved Standards, Recommended Practices, and Guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement between industry or trade, in general or specific, and AIAA to adhere to any AIAA standards publication and no commitment to conform to or be guided by standards reports. However, should a procuring authority choose to use this standard and contractually impose it upon a contractor or subcontractor, the use of this standard will be as defined by that particular contract.

In formulating, revising, and approving standards publications, the committees on standards will not consider patents that may apply to the subject matter. Prospective users of the publications are responsible for protecting themselves against liability for infringement of patents or copyright or both.

DRAFT

1 Scope

This standard defines terminology and establishes uniform processes, procedures, and systematic methods for the management, control, monitoring, determination, verification, and documentation of the mass properties during the design and development phases of space systems, including their components and subsystems. This standard applies to space vehicles (SV), upper stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles (LV), and ballistic vehicles. This standard is intended to be used as a reference for the development of a project-specific, contractually required mass properties control plan.

2 Tailoring

When viewed from the perspective of a specific program or project context, the requirements defined in this Standard may be tailored to match the actual requirements of the particular program or project. Tailoring of requirements shall be undertaken in consultation with the procuring authority where applicable.

NOTE Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Applicable Documents

The following document contains provisions which, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

4 Vocabulary

4.1 Acronyms and Abbreviated Terms

AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ATP	Authorization to Proceed
CAD	Computer Aided Design
CDR	Critical Design Review
CDRL	Contract (Deliverable) Data Requirements List
CFE	Customer Furnished Equipment
CM	Center of Mass
CR	Customer Reserve
DID	Data Item Description
ECLSS	Environmental Control and Life Support System
FEM	Finite Element Model

DRAFT

GSE	Ground Support Equipment
I&T	Integration and Test
LV	Launch Vehicle
MGA	Mass Growth Allowance
MIL-STD	Military Standard
MOI	Moment of Inertia
MPE	Mass Properties Engineer
MPCB	Mass Properties Control Board
MPCP	Mass Properties Control Plan
NASA	National Aeronautics and Space Administration
NRO	National Reconnaissance Office
NTE	Not to Exceed
ORD	Operational Requirements Document
PDR	Preliminary Design Review
POI	Product of Inertia
PSRR	Pre-shipment Readiness Review
SAWE	Society of Allied Weight Engineers, Inc.
SC	Spacecraft
SWI	Standard Work Instruction
TP	Test Procedure
TPM	Technical Performance Measurement
TRL	Technology Readiness Level
TRD	Technical Requirements Document
TRR	Test Readiness Review
WBS	Work Breakdown Structure

4.2 Terms and Definitions

For the purposes of this document, the following terms and definitions apply. Figure 1 provides a graphical summary of the relationships between key definitions below. Annex A provides mathematical representations of a number of the terms defined below as well as vehicle-specific graphical summaries of the relationships between key definitions.

Bus
the part of a space system which supports payloads

DRAFT

NOTE The bus includes the structure, power subsystem, attitude and control subsystem, propulsion subsystem, telemetry subsystem and communication subsystem.

Basic Mass
the current mass data based on an assessment of the most recent baseline design

NOTE 1 This design assessment includes the estimated, calculated, or measured (or actual) mass, and includes an estimate for undefined design details.

NOTE 2 The basic mass is also referred to as “Nominal” or “Current Best Estimate” mass. To unify the terminology and avoid confusion, “basic mass” is used in this standard instead of “Nominal” or “Current Best Estimate.”

NOTE 3 The mass growth allowances (MGA) and uncertainties are not included in the basic mass.

Center of Mass (CM)
the point that represents the mean position of the matter in a body

Critical Mass Properties
those mass properties parameters that have limits which would jeopardize mission performance if exceeded

Customer Reserve (CR)
the mass budget reserved by the customer for out-of- scope changes

EXAMPLE Additional payload added with requirements not included in the original proposal

NOTE 1 Customer reserve includes the dry mass for the added items plus the additional propellant mass required for the CR items.

NOTE 2 The customer will define the CR based on the confidence level to the launch vehicle (LV) performance and requirement to provide relief to the contractor according to the agreements of the contract.

In-Scope Changes
design modifications implemented by the contractor to meet contractual requirements

NOTE Item 1 and Items 3 through 9 in Table 3 are in-scope changes.

Mass
the quantity of matter in a body which serves as a measure of the body’s translational inertia

Mass Growth Allowance (MGA)
the expected increase in the basic mass of an item based on an assessment of the design and fabrication status of the item, and an estimate of the design changes that may still occur

NOTE 1 These design changes are changes that may be implemented by the contractor to meet contractual design requirements during the design process. The MGA associated with these design changes generally compensates for the lack of design maturity and the lack of manufacturing tolerance information. MGA compensates for potentail in-scope changes only. Customer Reserve should be used to compensate for potential out-of-scope changes.

NOTE 2 Table 1 provides a Mass Growth Allowance and Depletion schedule for use by the contractor.

Mass Margin
the difference between the space system allowable mass and predicted mass

Mass Properties Control Board (MPCB)
a body tasked to produce a minimum mass design consistent with mission requirements and to identify risks to the overall program resulting from any non-compliance with mass properties requirements

NOTE 1 Members typically consist of representatives from the Program Office, Systems Engineering, Stress, Thermophysics, Dynamics, Survivability, and from each subsystem area.

DRAFT

NOTE 2 The MPCB may be referred to by different names (e.g., Weight Control Panel, Mass Properties Working Group, etc.) by different organizations.

Moment of Inertia (MOI)
the rotational inertia or resistance to change in direction or speed of rotation about a defined axis

Out-of-Scope Changes
design modifications (See Item 2 of Table 3) that are not in line with the current contract baseline, but for any number of reasons may be considered in the future

Payload
spacecraft-manifested subsystem which performs a function or functions not directly related to spacecraft basic operations or maintenance

Predicted Propellant Mass
the mass of propellant, including residuals and loading/operational uncertainties, necessary to meet propulsion requirements

NOTE Calculated using the space system predicted dry mass.

Predicted Mass
the basic mass plus the mass growth allowance

Product of Inertis (POI)
a measurement of a body's dynamic (or coupled) imbalance resulting in a precession when rotating about an axis other than the body's principal axis

Space System
a system designed to exist in space including space vehicles (SVs), upper-stage vehicles, injection stages, satellite payloads, reentry vehicles, launch vehicles (LVs), ballistic, or other vehicles

NOTE Space systems do not include Ground Support Equipment.

Space System Allowable Control Dry Mass
a "not to exceed" (NTE) value derived from the LV capability minus the LV interface adapter, including mission-peculiar items, and minus the customer reserve and the total propellant (including gases) required for the complete mission

NOTE The space system predicted dry mass is typically controlled to less than the SV allowable dry mass.

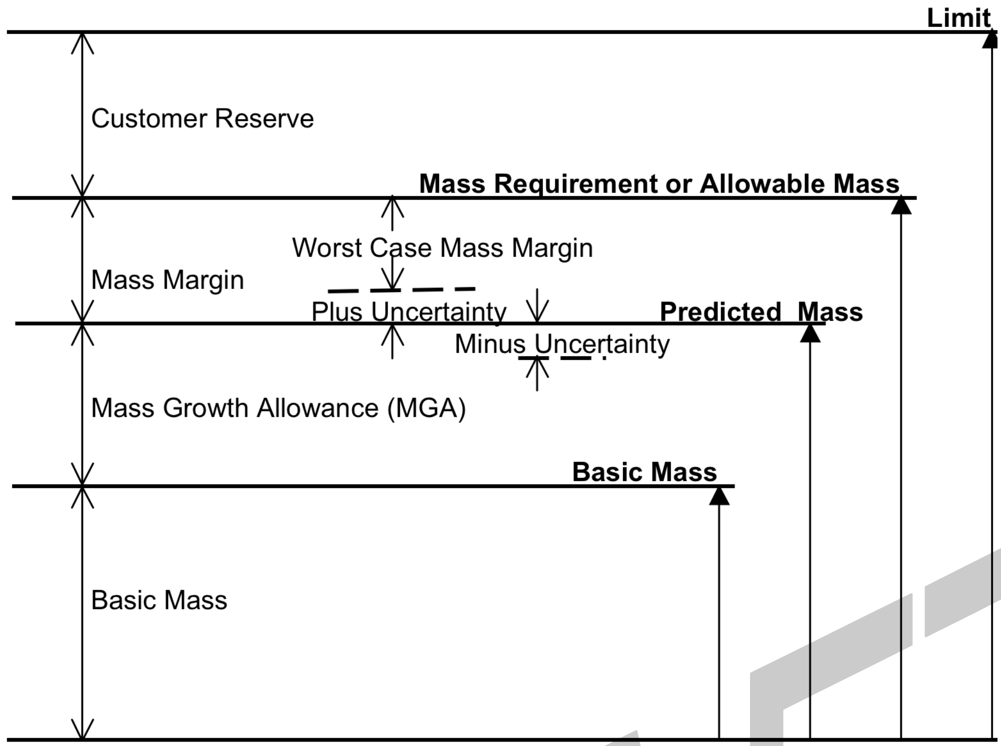
Space System Wet Mass Properties
The SV predicted dry mass properties plus customer reserve plus the total required propellant is equal to the predicted mass properties at separation. SV wet mass plus the SV/LV interface adapter mass properties including the mission peculiar items are equal to the SV wet mass properties at launch.

Uncertainty
variation in mature (actual) hardware mass properties due to inability to measure hardware or fluids or manufacturing variations

NOTE Mass growth is not typically included

Weight
the force that results from the action of gravity on matter

NOTE Weight is the product of mass and local gravitational acceleration. In practice, weight is what is measured at the surface of the earth.



NOTE Mass Margin is Allowable Mass minus the Predicted Mass. Worst Case Mass Margin is Allowable Mass - (Predicted Mass + Uncertainty)

Figure 1 — General Mass Definitions

5 Requirements

5.1 Mass Properties Control

5.1.1 Scope

The mass properties control program for space systems shall be in accordance with the requirements of this standard. The program level of effort shall be adequate to determine, control, and document the mass properties of the space system, subsystems, and components. The mass properties control program includes all subcontractor items, associate contractor items, and Customer Furnished Equipment (CFE) items, as well as contractor-furnished items.

5.1.2 Mass Properties Control Plan

The contractor shall develop and document a mass properties control plan (MPCP) for the space system to state the management plan and the procedures for mass properties control and verification during the various procurement phases. The MPCP describes in detail the formal process for controlling mass within the Program/Project organizational structure and includes the applicable requirements specified in Section 5 of this standard..

5.1.2.1 Objective

The objective of this plan shall be to formulate an organized mass properties control program based on the critical parameters that can be effectively controlled and implemented in the contract to meet the space system mass properties requirements.

DRAFT

5.1.2.2 Contractor Program Management Responsibility

Contractor management at all levels (Program Manager, Chief Engineer, Integrated Product Team Leader, System Engineering Leads, Mass Properties Lead) shall participate in the development and maintenance of the mass properties control program and support mass-efficient design, thereby building a foundation on which an effective mass control program can be built.

5.1.2.3 Personnel

Personnel shall be assigned the responsibility and authority to assure the establishment and maintenance of mass properties objectives and the effective planning and execution of mass properties control functions. Engineering design managers are responsible for controlling their respective subsystem designs within mass allocations, initiating mass reduction activities when directed by the Mass Properties Control Board (MPCB), and reporting mass-impacting design changes to the mass properties engineers and the MPCB. Mass properties control therefore is <u>not</u> only a function of the MPCB, but is a responsibility of every member of the design team.

5.1.2.4 Subcontractor Mass Properties Control Plan

The contractor shall be responsible for the mass properties control of each subcontractor and vendor. In each procurement document, items which affect the space system mass properties to a significant extent (as determined by the responsible MPE) shall include a mass properties control section to impose the applicable requirements of this document on the subcontractor or vendor.

NOTE Mass properties control may be applied as appropriate for items with known mass properties.

5.1.2.5 Subcontractor Design Activity and CFE Suppliers Interfaces

Subcontractor Design Activities and Customer Furnished Equipment (CFE) suppliers shall be responsible for the interchange of sufficient mass properties data to support the integration of subunit mass properties into the complete unit mass properties and shall promptly respond to requests from the interfacing and integrating contractors for information required by the contractors in satisfaction of contractual requirements.

5.1.3 Mass Properties Control Process

The mass properties control process begins with a clear understanding of the mass properties requirements and an estimate of predicted performance to assess compliance to requirements. The contractor shall develop achievable mass properties objectives and shall assist the procuring activity in specifying general system mass properties requirements and their proper allocation to the configuration element requirements. During the initial development of, or any subsequent change to, mass properties objectives, the contractor shall give particular attention to substantiating data, mass properties dependent design performance information, and the critical mass properties uncertainties analysis.

5.1.3.1 Requirements Flow-down and Traceability

The contractor shall perform a comprehensive review of all program system requirements and identify all the major mass properties requirements that affect space system performance. The source of the requirements starts with the contractual Technical Requirements Document (TRD) or Operational Requirements Document (ORD), the flow-down of requirements to the space system subsystems and components, and includes internally derived requirements imposed on the space system from specialty engineering functions such as Attitude Control, Mission Engineering and Ground Handling and Transportation. The contractor shall show the traceability to its source for each requirement. The contractor shall prepare a verification cross-reference matrix showing the mapping between each requirement and the method(s) to be used for verification of the requirement.

DRAFT

5.1.3.2 Assessment of Predicted Mass Properties Against Requirements

The contractor shall perform an analysis to show predicted performance for each identified critical mass properties requirement that affects space system performance, and verify compliance. The predicted mass properties shall include the basic (nominal) value plus the predicted growth and adverse uncertainty based on an assessment of design maturity. The contractor shall initiate a recovery plan when negative margins are predicted.

5.1.3.2.1 Basis for Mass Properties Confidence

The percent of the space system mass that is based on each of the categories in Table 1 is an indication of the confidence that shall be placed in the mass properties data.

5.1.3.2.2 Mass Properties Categorization Guidelines

The maturity code of each component mass shall be included as part of the recorded component data. As many categories as are necessary to accurately define the status of the mass properties may be used. Totals of each of these categories shall be recorded to provide an indication of the mass properties confidence at the subsystem level for the major subsystems and the complete system.

5.1.3.2.3 Mass Growth Allowance and Depletion Schedule

The contractor shall include in the mass data an allowance for the expected mass growth resulting from lack of maturity in the current design data. Mass growth varies as a function of hardware and its design maturity. The mass growth allowance shall be applied at the lowest design detail level reported in the mass properties database. Depletion of the mass growth allowance follows the design process; as the design and analyses of the hardware matures, the mass growth allowance depletes to reflect increased confidence in the predicted final mass. If the contractor does not have its own mass growth and depletion schedule, the contractor shall use Table 1 (Mass Growth Allowance and Depletion Schedule) to determine MGA.

DRAFT

Table 1 — Mass Growth Allowance and Depletion Schedule

Code	Design Maturity (Basis for Mass Determination)	Percent Mass Growth Allowance													
		Electrical/Electronic Components			Structure	Brackets, Clips, Hardware	Battery	Solar Array	Thermal Control	Mechanisms	Propulsion	Wire Harness	Instrumentation	ECLSS, Crew Systems	Solid Rocket Motor Inerts
		0-5 kg	5-15 kg	>15 kg											
E	**Estimated** 1) An approximation based on rough sketches, parametric analysis, or undefined requirements, or 2) a guess based on experience, or 3) a value with unknown basis or pedigree.	30	25	20	25	30	25	30	25	25	25	55	55	23	10
L	**Layout** 1) A calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) Major modifications to existing hardware	25	20	15	16	20	15	20	20	15	20	30	30	18	6
P	**Preliminary Design** 1) Calculations based on a new design after initial sizing but prior to final Structural or Thermal analysis, 2) minor modification of existing hardware	20	15	10	12	10	12	15	15	10	15	25	25	12	4
R	**Released Design** 1) Calculations based on a design after final signoff and release for procurement or production, 2) Very minor modification of existing hardware	10	5	5	5	3	5	5	4	4	5	10	10	9	3
X	**Existing Hardware** 1) Actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes, 2) Values based on measured masses of qualification hardware	3	3	3	4	2	3	3	2	2	3	5	5	4	1
A	**Actual Mass** Measured hardware	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S	**Customer Furnished Equipment or Specification (not to exceed) Value**	0	0	0	0	0	0	0	0	0	0	0	0	0	0

DRAFT

5.1.3.2.4 Mass Properties Uncertainties/Tolerances

Mass properties uncertainty analyses shall be conducted when mass properties dispersions are required for other analyses, or when the uncertainties may cause mass properties limits to be exceeded. The uncertainty analysis shall include a detailed analysis of each uncertainty source with a description of the derivation of the uncertainties. The uncertainties analysis for measurements, manufacturing variations, and environmental effects shall not include MGA; however, uncertainties associated with estimations or calculations shall include MGA. If mass growth is included in the analysis, an explanation of how it is combined with the other sources of uncertainty is required.

5.1.3.2.5 Mass Threats and Opportunities and Probability of Occurrence

The assessment of mass properties predicted performance must also consider potential changes to the design that may adversely impact predicted mass properties margin against requirements. The contractor shall evaluate the magnitude of, and document the status for, each potential design change assigned a high probability of impact on compliance with requirements. The evaluation of mass threats and opportunities shall include an assessment of the impact to predicted propellant mass. Each potential change shall be evaluated and assigned a percent probability of occurrence as either: “High” (H) (above 75%), ”Medium” (M) (between 25% and 75%), or “Low” (L) (less than 25%). The contractor shall evaluate and document status for each potential design change assigned a “high” probability for impact on compliance with requirements.

5.1.3.2.6 Mass Margin

Mass margin is defined as the difference between the allowable mass and the predicted mass. This margin is a measure of the contractors’ ability to mitigate the risk of underestimating predicted mass or overestimating predicted subsystem performance. This margin also is meant to mitigate potential mass increases from omissions or refinement of existing requirements. Mass margin must cover the upper limit of the sum of the predicted mass and the mass uncertainty. Mass margin is not to be confused with Mass Growth Allowance (MGA), which is used in estimating predicted mass.

Customer Reserve is another form of mass margin, held by the customer for mitigating new requirements.

The recommended amount of total mass margin, which is the difference between mission limit and predicted mass, varies depending on the complexity of the space system, and the customer’s confidence that he can meet the mission limit. Additional consideration should be given to budget, schedule and reliability requirements when considering the minimum acceptable total mass margin. Based on historical mass growth and the MGA schedule in Table 1, Table 2 can be used as a guideline.

5.1.3.2.7 Technical Performance Measurement (TPM)

The contractor shall track and status all critical mass properties parameters (including mass, CM, MOI, and POI) using TPM charts that show basic and predicted performance against derived limits and contractual requirements. An example of a TPM for assessing mass compliance by program phase is exhibited in Table 2. A graphical representation of basic mass, MGA, and margin versus time is presented in Figure 2.

5.1.3.2.7.1 Determination of Limits

Throughout the contract period, the contractor shall determine and document the mass properties limits for each critical requirement. The mass properties limits shall include those established by system, subsystem, and component performance, as well as design requirements and the mass properties limits established by contract. These control limits shall be applied to the appropriate TPM charts to show predicted performance margin against the requirement. Table 2 uses historical data gathered from more than 40 programs. The dispersion of the data has been coalesced into an “average” program. For programs with a preponderance of new hardware, or conversely, those using mainly existing hardware,

DRAFT

the contractor would need to adjust the percentages in Table 2 upwards for the former, and downwards for the latter.

5.1.3.2.7.2 Trend Analysis Monitoring

By analyzing the trend in the TPM charts, an early warning of potential problems can be acted on. This trend analysis is particularly critical prior to the program preliminary design review (PDR), when designs are still evolving, in order to minimize cost and schedule impacts for changing the design to fix non-compliant parameters. Figure 2 is a classic example of MGA and margin trends, plotting over time how the basic mass approaches the contractor limit as the program matures. The percentages from the average program of Table 2 have been inserted at the appropriate milestones in Figure 2.

Table 2 — Example TPM Chart for Mass

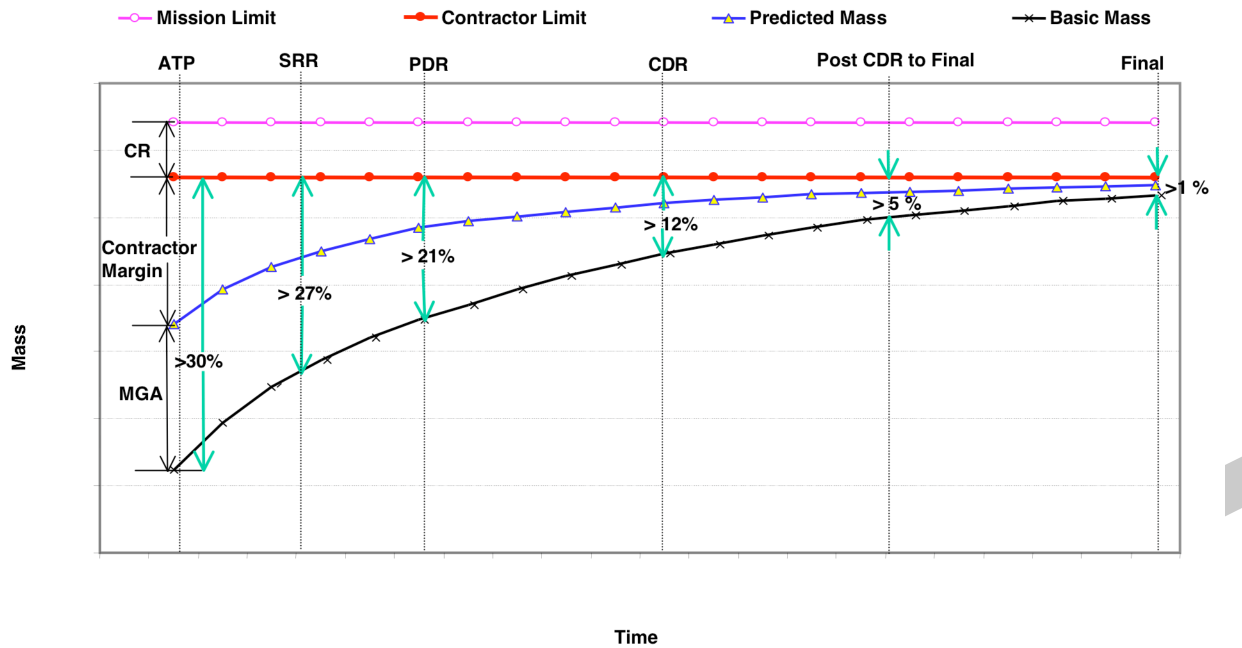
Program Milestone	Mass Growth Allowance		Recommended Mass Margin	
	(%)[1]	Grade	(%)[1]	Grade
ATP	> 15	Green	> 15	Green[2]
	9 < TPM ≤ 15	Yellow	10 < TPM ≤ 15	Yellow
	TPM ≤ 9	Red	TPM ≤ 10	Red
SRR	> 15	Green	> 12	Green
	9 < TPM ≤ 15	Yellow	6 < TPM ≤ 12	Yellow
	TPM ≤ 9	Red	TPM ≤ 6	Red
PDR	> 12	Green	> 9	Green
	8 < TPM ≤ 12	Yellow	5 < TPM ≤ 9	Yellow
	TPM ≤ 8	Red	TPM ≤ 5	Red
CDR	> 7	Green	> 5	Green
	4 < TPM ≤ 7	Yellow	3 < TPM ≤ 5	Yellow
	TPM ≤ 4	Red	TPM ≤ 3	Red
Post CDR[3]	> 3	Green	> 2	Green
	2 < TPM ≤ 3	Yellow	1 < TPM ≤ 2	Yellow
	TPM ≤ 2	Red	TPM ≤ 1	Red
Final	0		> 1	

[1] The percentages of MGA and Margin in the above chart are defined as follows:

MGA = predicted dry mass - basic dry mass
% of MGA = (MGA/basic dry mass) * 100
Dry Mass Limit = mass limit – propellant mass
% of Margin = [(dry mass limit – predicted dry mass)/predicted dry mass] * 100

[2] There is a 50% chance that an average program will not exceed the sum of the MGA and the margin.

[3] Post CDR is halfway between CDR and final delivery.



Note: The Figure above represents the percentage of mass growth to the "Basic Dry Mass".
% of MGA and Margin = [(MGA+Margin) / Basic Mass] x 100
= [(Contractor Dry Mass Limit – Basic Mass) / Basic Mass] x 100

Figure 2 — Sample Plot of Mass Versus Time

5.1.3.3 Mass Properties Control Board (MPCB)

The contractor shall implement a Mass Properties Control Board (MPCB) to affect a minimum mass design consistent with mission requirements and to identify risks to program for any non-compliance to mass properties requirements. An example of the MPCB composition and process is shown in Figure 3.

5.1.3.3.1 Program Management Responsibility

The MPCB, under program management leadership, is the key mass properties management decision making authority on the program, and is responsible for the administration and management of all mass properties control activities directly affecting the space system design. The program management, or designee, is responsible for providing direction to the space system teams to fully support the functions of the MPCB.

5.1.3.3.2 Placeholder to keep section numbers consistent while editing

5.1.3.3.3 Key Functions of the Board

The key MPCB functions shall include, but are not limited to, the following:

— Approve the Mass Properties Control Plan and subsequent revisions.

— Establish not-to-exceed (NTE) mass properties control limits (allocations) at the space system, subsystem, and unit level, and approve all subcontractor specification mass properties.

— Direct audits of the mass properties database to verify that the current mass properties accurately reflect the current design configuration.

— Assess proper assignment of mass growth allowance based on design maturity.

- Assess adequate mass properties margins and, if not sufficient, define and initiate a recovery plan.
- Generate and maintain a comprehensive list of opportunities to reduce mass with estimates for cost, schedule, and performance impacts to support a program decision to implement.
- Establish a dollar value per kilogram of mass savings.
- Evaluate potential design changes with threats to increase and opportunities to decrease the system mass and assign probability of occurrence (High, Medium, and Low) and assign a decision-making date for implementation. Review and update the decision date at MPCB meetings.
- Provide risk assessments and recommended risk mitigation actions.
- During full-scale development, the MPCB, as a minimum, reviews the following:
  - The status of action items from the previous MPCB
  - Current space system mass
  - Changes to current mass
  - Reasons for changes
  - Mass maturity status
  - Mass growth trends of the subsystems, bus, payload, and space system
  - Critical mass properties requirements
  - Pending and potential changes
  - Launch Vehicle performance and control limits

5.1.3.3.4 MPCB Process Flow Chart

Composition and process of the MPCB is shown in Figure 3 as an example.

DRAFT

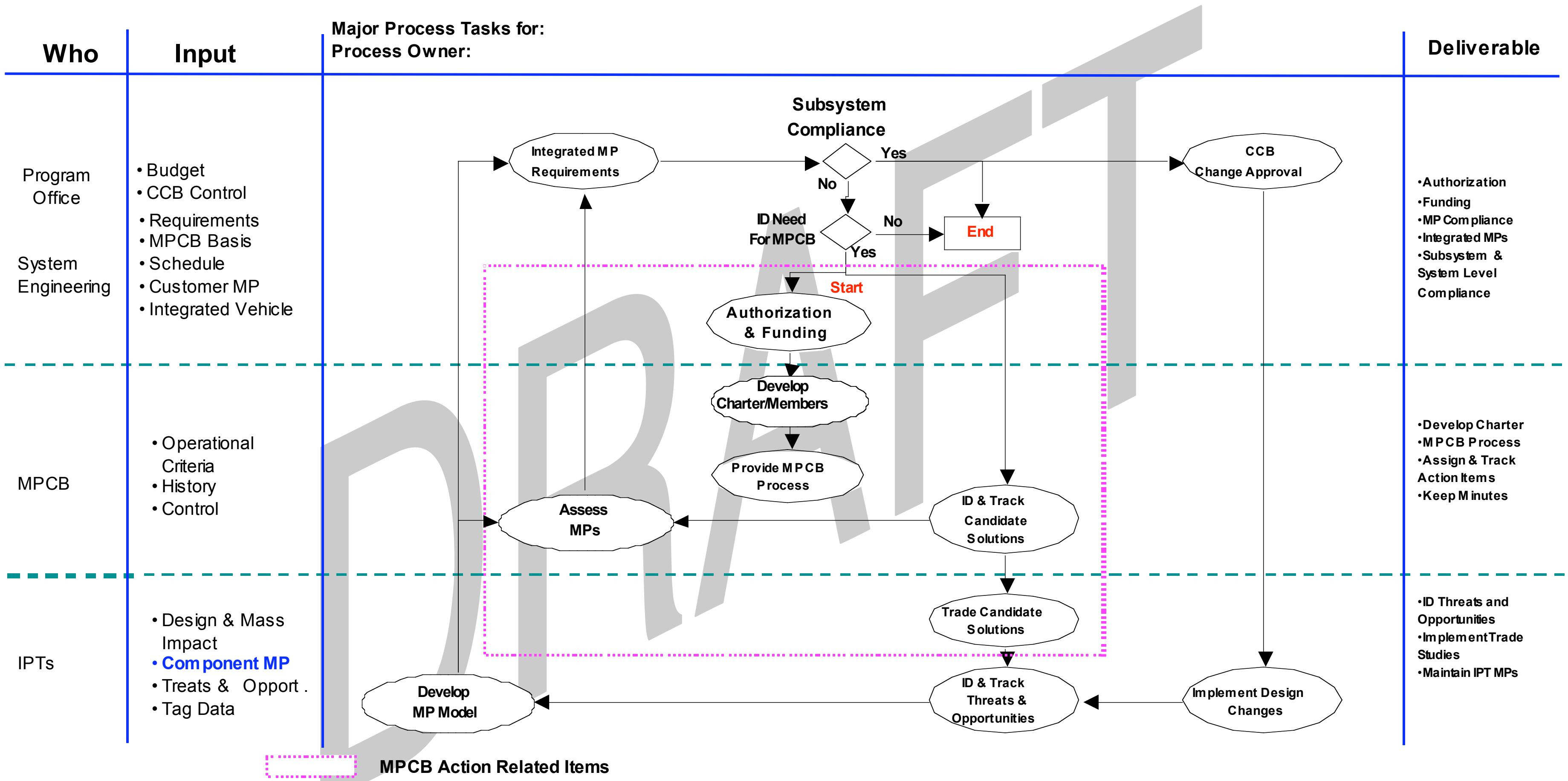


Figure 3 — Example Mass Properties Control Process

5.1.3.3.5 Reporting

The Mass Properties Lead Engineer of the MPCB, or designee, shall document all approved engineering mass changes, decisions, and actions in MPCB minutes and distribute in softcopy format to all members of the program team. The minutes for each separate MPCB meeting shall be maintained in the form of electronic records throughout the program duration.

5.1.3.4 Placeholder

5.1.3.5 Mass Properties Monitoring

Monitoring of the space system mass properties parameters is required by all program personnel and teammates responsible for delivery of flight hardware to the space system to meet system mass properties requirements. The contractor mass properties personnel have the assigned responsibility for accurate mass properties determination, monitoring of the design, and timely reporting to support the mass properties control tasks on the program and to ensure delivery of hardware compliant with all mass properties requirements. To achieve this goal, the MPCB shall set internal mass properties allocations at the subsystem and unit level consistent with their respective top-level mass properties allocation requirement. Each member of the program team shall be aware of their mass properties allocations and limits and provide compliance status to the mass properties activity through the design drawing release phase.

5.1.3.6 Drawing Release Sign-Off

Documents controlling the design, manufacture, and procurement of system components shall be approved, prior to release by personnel responsible for the contractor's mass properties control effort. Such approval shall signify component acceptability in satisfaction of system mass properties objectives and the currency of the mass properties accounting system.

5.1.3.7 Trade Studies

Adequate methodology and tools shall be developed, or existing methodology and tools adapted, to support trade studies involving mass properties inputs. Such methodology and tools may be curves, computer programs, or any suitable means for relating major design parameters to significant mass properties and providing parametric assessment of inter-system and intra-system mass properties during trade studies leading to item selection. The contractor shall determine and maintain, in a form available for review by the procuring activity, the following: (1) the mass properties considered in the trade studies and other screening processes for including or excluding designs for future study, and (2) the net effect on mass properties if the trade study recommendations are implemented.

5.2 Analysis Plan

5.2.1 Scope

The mass properties analysis plan shall support the program requirements for space system mass properties accuracy and documentation for all configurations throughout the mission. The contractor shall determine the scope of the mass properties analyses required and implement a plan to satisfy compliance with all of the program mass properties requirements. The contractor shall ensure that personnel with sufficient mass properties training and experience are assigned the responsibility to perform the required analyses and that adequate analysis tools are available to predict space system mass properties through all phases of the program. The contractor shall maintain adequate documentation of the analyses to substantiate the accuracy and completeness of the space system mass properties model throughout the program phases from proposal to launch.

5.2.2 Methods of Analysis

The primary methods of analysis are typically dictated by the program phase; however, the content of the analysis during each program phase, from proposal to launch, shall clearly include the maturity level of the analytical mass properties model. The maturity level is best defined by the percent of the space system mass categorized for each maturity code (as described in 5.1.3.2.2). The early phases of program acquisition and development, specific proposal, and contract award through system PDR are critical because historical data indicates half of the mass growth experienced on the average program occurs during this period. The reasons for this observed mass growth are:

— lack of design maturity information,

— overly optimistic assessment of the hardware maturity,

— requirements that are not fully defined/understood or flowed down to the subsystem/unit levels.

During this early phase, the contractor shall substantiate the mass properties model and MGA values used by providing a maturity assessment of each subsystem/and key component. This assessment shall be accomplished by defining the heritage for each detail of the flight hardware using the categories provided in Table 1. When parametric scaling techniques are used, the contractor shall provide historical data to support these methods.

5.2.2.1 Parametric Analysis

Between proposal and system PDR, the contractor may prepare a parametric analysis to substantiate the accuracy of the space system and components mass estimate. The parametric analysis is based on the historical performance from previous programs using analysis techniques such as empirically derived parametric scaling of data. Prior to PDR, the parametric analysis should be replaced by a bottom-up analysis based on design requirements and loads analysis.

5.2.2.2 Manual Layout/Drawing Analysis

The contractor shall document and maintain records of the manual calculation of mass properties data from design layouts and drawings. This data shall be organized by drawing or part number and show roll-ups from lower level details to assembly and subsystem definitions.

5.2.2.3 Computer-Aided Design Analysis

The primary method for space system flight hardware mass properties analysis during the design and drawing release phase shall be based on the available computer-aided design (CAD) tool. The contractor shall be cognizant and responsible for accounting for the mass properties of all items that are not modeled as solids in the CAD tool. Examples of these items could be thermal finishes (primer, paint), structural adhesives, wire harness, fluids. The contractor shall document the current CAD's design mass properties at the detail level. Special attention shall be paid to understanding whether a positive or negative integral is used in the determination of the products of inertia values from the CAD's tool. The products of inertia values specified in the program mass properties model assume a positive integral. Use of the wrong sign convention may result in principal axis errors that can affect flight dynamics.

5.2.3 Analysis Parameter Requirements and Recording of Analysis

The contractor shall perform the necessary analyses to fulfill all the mass properties requirements on the program and maintain documentation of the analyses to substantiate that the predicted performance meets requirements.

5.2.3.1 Mass Properties Parameter Requirements

As a minimum, the mass properties parameters required for analysis of space system components shall consider mass, center of mass, moments of inertia, and products of inertia.

DRAFT

5.2.3.2 Drawing Number or Part Number

The contractor's analysis of the space system detail components, assembly, and installation level definition shall include drawing number or part number.

5.2.3.3 Hardware Design Maturity Assessment

The contractor shall assign a hardware maturity assessment based on the codes in the MGA Depletion Schedule. The mass properties personnel shall be responsible for verifying that the proper assignment of maturity level is applied to each space system component.

5.2.3.4 Section Heading Placeholder (Deleted 5.2.3.4 Text)

5.2.4 Flight Hardware Analysis

All new or modified components, units, and subsystems are subject to detailed analysis. The contractor's mass properties personnel shall verify that the space system mass properties analysis is accurate and complete, including that of the subcontractors and teammates.

5.2.4.1 Correlation to Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS) is a hierarchical outline of the work to be done on the program or contract, along with a dictionary defining each entry in the outline. The contractor's flight hardware mass properties records shall correlate to the program contract work breakdown structure. This shall be done at a level of detail that permits the determination that the masses of all items on the space system have been included properly.

5.2.4.2 Remaining Test Instrumentation

All test instrumentation or GSE that remains with the space system through launch or operation shall be controlled as flight hardware and shall be included in the mass properties model.

5.2.4.3 Mass Changes

A documented accounting of all mass changes shall be maintained throughout the contract. For all mass changes, the accounting shall include the "was" and "is" value of the item, the magnitude of the change, and the reasons for the changes. Each mass change in the accounting shall be identified. This accounting shall be updated when the mass properties are updated. The mass changes shall be gathered into the categories defined in Table 3 and accumulated throughout the Program.

DRAFT

Table 3 — Mass Change Codes and Definitions

Code	Description
1	**Better definition of the design** (Design maturation) As the design progresses beyond the proposal stage, the design criteria and requirements become better defined. These changes are generally early in the program but prior to drawing release.
2	**Out of scope changes** These are new scope changes caused by the customer adding or changing the requirements for the contracted vehicle beyond that required by the existing contract.
3	**Redesign** When the original component or subsystem design criteria need to be changed due to repackaging, failure of a component during testing, impact of other subsystem changes, etc.
4	**Maturing component design** Improvements in mass analysis due to updates in drawings at or after original release. (Item #1 generally relates to mass analysis prior to drawing release.)
5	**Error in previous estimate** The reason for change is an error in the mass calculations for an original or later estimate.
6	**Uncontrolled vendor changes** If none of the other change codes apply, then this category is a catchall for vendor mass changes over which you have very little control.
7	**Mass reduction activity** Changes due to official mass reduction efforts.
8	**Measured vs. calculated** The differences caused by actual measured mass of components as opposed to the latest calculated value.
9	**Cost reduction or schedule reduction, added mass** Where mass increases were incurred to save time or money, i.e., substitution for expensive exotic materials, machinery costs reduced by eliminating elaborate machined parts and cutouts, etc.

5.2.5 Special Analyses

Special analyses may be required to determine tolerances or uncertainties on mass properties parameters to predict worst-case bounds and show compliance to requirements. Special analyses may be requested by internal customers, such as Structural Analysis, Mission Engineering/Dynamics/Control, Ground Support & Transportation Operations, or Payload Layout Design.

5.2.5.1 Mass Properties Uncertainty Analysis

Knowledge is required of the accuracies of mass properties data used in space system performance, stability, control, and structural analyses. This is true not only for the total space system but also for elements of the space system such as fluids and deployable and independently moving parts. Mass properties approaching a limit may require an uncertainty analysis. In some cases, the accuracy of the combination of certain mass properties may be required, such as an inertia ratio (spin to transverse moments of inertia ratio) or the inertia asymmetry, the difference of two transverse principal inertias.

DRAFT

5.2.5.1.1 Requirements for Uncertainty Analysis

Mass properties uncertainty analyses shall be conducted when mass properties dispersions are required for other analyses or when the uncertainties may cause mass properties limits to be exceeded.

5.2.5.1.2 Content of Uncertainty Analysis

The uncertainty analysis shall include a detailed analysis of each uncertainty source with a description of the derivation of the uncertainties. The uncertainties shall include, but are not limited to, measurement uncertainties, manufacturing variations, environmental effects, and uncertainties derived or assumed for mass properties estimations or calculations. If mass growth is included in the analysis, an explanation of how it is combined with the other sources of uncertainty is required.

5.2.5.2 Finite-Element Model Mass Distribution Analysis

The mass properties function shall provide a sectional mass distribution analysis, consistent with the segment definitions set by the structural and controls systems analysis group, to support the development of the space system finite-element model (FEM). The FEM supports analyses to determine dynamic response, loads distribution, stress analysis of structure and units, and control and stability limits for space system components.

5.2.5.3 Balance and Ballast Mass Analysis

The contractor shall consider the optimum locations and configuration of the balance and ballast mass required to meet the CM, static, or dynamic balance, and moment of inertia requirements for the space system. Equipment layout trades shall be considered to minimize the total amount of balance or ballast mass required. Analyses shall be performed to define the maximum amount of mass allowed at each balance or ballast mass.

5.2.5.4 Mission and Attitude Control Systems Analysis

Space system on-orbit operations require special consideration for determination of propellant location, mass properties of movable objects in the fixed and deployed configurations, and sequential mass properties of the space system configuration from launch to on-orbit operations, and to de-orbit.

5.2.5.4.1 Propellant Budget Modeling

The contractor shall calculate the propellant mass properties based on the space system predicted dry mass. The contractor shall have the ability to model the location of the propellant mass in the propellant tank(s) as a function of propellant fraction fill and mission condition (e.g., launch or spin field). The effective inertia of the propellant shall be estimated.

5.2.5.4.2 Movable Objects

The mass properties of moveable objects shall be determined for their nominal stowed and deployed conditions, as well as any intermediate positions that may be critical for stability and control concerns. The pivot point locations in the space system coordinate frame for each movable object shall be noted in the space system mass properties model. The order of rotations and translation of the movable object in its local coordinate frame shall be noted in the space system mass properties model.

5.2.5.4.3 Mission Sequential Mass Properties

The space system mass properties shall be determined and documented as a function of time or percent of tank fraction fill from mission initiation through mission completion. Time increments shall be selected based on requirements of other analyses or on significant mission events. All items that are expended, jettisoned, or moved during the mission shall be identified in the contractor's mass properties records.

DRAFT

5.2.5.4.4 Mission Worst-Case Analysis

In order to guarantee space system performance throughout the mission, a worst-case mass properties analysis may be requested periodically. The contractor shall have the capability to perform this analysis, which shall take into account extremes of mass, centers of mass, and inertias, as well as MGA, mass threats/opportunities, and margins (both dry mass and propellant).

5.2.6 Ground Operations Support Analysis

Adequate mass properties shall be developed and documented for the support of ground, transportation, and launch operations. These data shall be in agreement with the actual vehicle configuration and with the planned loading and utilization of fluids and propellants. The contractor's records of all changes to the space system subsequent to final mass properties measurements and the resulting mass properties shall be made available for review.

5.2.7 Post Flight Analysis

Actual mass properties data should be determined by analysis of post-flight data, where available, for significant mission events. Differences from the planned conditions shall be itemized and explained.

5.2.8 Breakup Analysis/Disposal

Mission analysis may require a plan to deorbit or reposition a space system at the end of its operational life. Furthermore, a space system may malfunction and pose a threat to life and property. In these scenarios, the mass properties of the system or subset of the system must be known. The contractor shall have the capability and flexibility to provide accurate mass properties when given specific configurations to track.

5.3 Verification

5.3.1 Verification Plan

The contractor shall develop and document a verification plan to describe and substantiate the methods to verify the mass properties conformances to their requirements. The verification plan shall be originated from the conceptual design and development stage, updated and reviewed at PDR, and released by CDR.

5.3.1.1 Verification Criteria

The contractor shall first define the verification criteria based on flow-down requirements to:

— identify those mass properties parameters requiring verification—mass, center of mass (CM), moments of inertia (MOI), or products of inertia (POI);

— describe the accuracies required for above parameters to comply with requirements;

— select verification methods that are consistent with the mass properties requirements;

— provide a matrix to list the parts or units, subassemblies, assemblies, bus, payload, and space system to be verified along with mass properties parameters, verification methods, required accuracies, and schedule.

5.3.1.2 Verification Method Selection

Verification may be accomplished by analytical methods (See 5.2 Analysis Plan), by measurement (See 5.3.2 Test Plan), or by a combination of both. The selection of the verification methods shall be justified by an approved verification plan. The verification methods shall be selected early enough in the program to provide time for the acquisition, modification, or preparation of test equipment and test site selection.

DRAFT

5.3.2 Test Plan

The test plan, a part of the verification plan, is required for documenting the mass properties to be verified by measurement. The test plan shall include the test description, requirements and success criteria, GSE requirements, measurement uncertainties, measurement schedule, data record, standard work instruction (SWI), and test procedure (TP). The responsible production integration and test (I&T) planner shall schedule the required mass properties measurements (based on test plan) in the planning book. The test plan shall include requirements for measuring mass, CM, and MOI, or for performing static or dynamic balance. The test plan shall outline the steps to be followed during test or, where practical, refer to the latest revision of the SWI or TP.

5.3.2.1 Test Description

The contractor shall list the test items, verify the test configuration, identify the mass properties parameters to be measured, state the test accuracy requirements, select the test equipment, and establish the test set-up. The detail test description is elaborated below as an example.

- Description of the Test Items—list the items to be measured, for example, the electronic units, detail parts, wire harness and cables, thermal blankets, mechanism, structure subassemblies, assemblies, payload, bus, and total space system. Provide the part numbers or drawing numbers and serial numbers for the test items.

- Verification—verify completeness of the test items using the parts list of the current revision drawings. Identify and record any missing items, non-flight items added, and tare items. Note the configuration status if the items are not in final flight status, e.g., engineering model or qualification unit.

- Mass properties parameters, required tests and success criteria—identify the required mass properties tests, such as mass, CM, MOI and POI, and static or dynamic balance. Provide the test requirements and success criteria.

- Provide a list of the measurement system and equipment to be used and the test location.

- Describe the test setup and outline the test steps to be followed by an approved SWI or TP.

- Include the pertinent dimensions, definition of the coordinate system, and reference datum.

- Include the environmental and safety control provisions.

5.3.2.2 Ground Support Equipment (GSE)

The contractor shall identify the required GSE for the measurements, including the test adapters, lifting fixtures, and sling cables with appropriate proof load and effective validation.

If new GSE is required, address the design and manufacturing schedule in the test plan. A test equipment fit check shall be planned, allowing adequate time for problem resolution so as not to impact the test schedule. If existing GSE is to be used, a fit check is required to assure that the GSE is in working condition. Allow adequate time to make modification as necessary. Test plan shall also include a schedule for GSE storage, transport to test site, and preparation in clean and working condition.

5.3.2.3 Measurement Uncertainty

The test plan shall include a statement of overall uncertainty of the measurement system with a measurement system error analysis. The measurement system analysis shall include all possible error sources, method of estimation, alignment tolerances, possible effect on the precision of measurement, and the method of combining different sources of error to obtain a value for overall uncertainty of the measurement process. The analysis shall also indicate the relationship between the uncertainty and the required accuracy.

DRAFT

Uncertainty analysis shall be included as a part of the test plan to determine the achievable test requirements. It shall be originated from the conceptual design and development stage, and updated at each program milestone (PDR, CDR, TRR, PSRR, at launch and post-mission analysis).

5.3.2.4 Measurement Schedule

The contractor shall provide a measurement schedule based on the program master phase plan and update the schedule at major milestones, estimate time required for each test based on past history averages, and prepare a test schedule flow chart. Sufficient time shall be allocated for the test to avoid rushing to completion, missing important test data, making mistakes, or jeopardizing safety. The contractor shall inform the appropriate personnel of the current measurement schedule.

5.3.2.5 Data Record

The mass properties verification data shall be documented. The test reporting plan, including submittal schedules, shall contain the minimum information as described in the following subsections.

5.3.2.5.1 General

Records for each major mass properties measurement performed in accordance with approved procedures or detailed work/process instructions shall include the following.

- An explanation of any deviations from approved procedures or work/process instructions.
- An evaluation of the measurement results with conclusions that state whether the mass properties measurements comply with their requirements. In cases where non-compliance to requirements is predicted, clearly define the technical performance impact for such and identify options to mitigate any technical performance shortfall.
- Test equipment model number and serial number.
- Location where measurements were performed, signature of authorized individual responsible for the entries, date and time of entries, date of last equipment calibration, document number of the approved measuring procedures, and identification of the item measured.
- Provision for the signature of the contractor's quality control representative on each page of the data record that includes measured data.

5.3.2.5.2 Records for Mass Properties Measurements

Records for mass properties measurements shall include the raw test data and the test data reduction methods used to derive the as-measured test results and the determination of the flight configuration. Prepare the following as applicable.

- Tables showing the applicable scale readings: tare; net mass; moment arm; moment for longitudinal, vertical, and lateral center of mass; and calculations showing the derivation of the "as-measured" mass and center of mass condition from the measurements.
- Measurements taken for the determination of moment and product of inertia and calculations showing the derivation of the "as-measured" inertias from the measurements.
- Variance Items—A list of items, including a Shortage List and an Overage list, for the mass, center of mass, moment of inertia, product of inertia, and data to be added to or subtracted from the "as measured" condition to obtain the actual mass properties determination for the flight condition.
- Diagrams of measuring equipment and related fixtures showing pertinent dimensions and other data required for the determination of the "as-measured" mass, center of mass, and moment and product of inertia.

DRAFT

5.3.2.5.3 Post-Test Configuration Change Log

Prepare and maintain a detailed record of all changes made, post-test, to the flight configuration for each critical mass properties measurement. The post-test change log shall include the following at a minimum.

— Description of the change and the mass properties parameters affected

— Quantify by measurement the "was" and "is" conditions for each mass properties parameter affected by the change

— Date of the change

— Signatures of the contractor's quality/configuration control representative and the responsible engineering activity for each configuration change

— Prepare records in a chronological order

5.3.3 Standard Work Instruction (SWI)

SWI shall be documented and included in the test plan, where applicable, to address the standard practice and general procedure for mass properties measurements. The SWI is usually applicable for routine standard mass properties measurements to be followed, e.g., SWI for mass and CM measurements, SWI for load cell calibration, SWI for electrostatic protection, etc. The SWI shall be referenced, where practical, in the test procedure.

5.3.4 Test Procedure (TP)

The test procedure is one of the important parts of the test plan when measurements are required for bus, payload, and space system-level mass properties tests, e.g., mass, CM, MOI measurements, and balance procedure for space system. Mass properties tests shall be conducted in accordance with approved and released detailed test procedures. A preliminary test plan shall be originated and reviewed at the program CDR.. The following paragraphs address the contents that must be included in the test procedure as a minimum.

5.3.4.1 Test Scope

The test scope describes the general plan for the test objective, test methods, and operation.

5.3.4.2 Applicable Documents, Equipment, GSE, and Software

The contractor shall list all applicable documents related to the test, including government documents, standards, specifications, a list of the associated equipment, GSE and software, related SWI, general practices, and procedures.

5.3.4.3 Requirements

The following requirements shall be included in the test procedure.

— Requirements for the mass properties test environmental conditions (test site cleanliness, temperature, humidity); operational tolerances and hazard class shall be addressed in the test procedure.

— Security requirements—security level of the test shall be printed on the front page, and corresponding escort, guard, and entrance regulations shall be addressed and followed as required.

— Requirements for mass properties test equipment calibration and tolerances shall be included in the mass properties test procedure.

— Quality assurance and Safety Health Environmental Affairs (SHEA) provisions shall be included in the mass properties test procedure. An initial or signature line shall be provided for those key steps that are critical for personnel or test item's safety and test results.

— Mass Properties test log requirement—a test log shall be part of the mass properties test requirement to record the mass properties test events and schedules. Note all necessary test information to pass them to the next shift team and record all anomalies and important test data during test. The test log shall be kept up to date.

— Mass properties requirements shall be defined in the test procedure to determine the success criteria for test.

— Document flow down of test requirement to as tested condition. The derivation of the test requirements can be either included in test procedure or in a separate document with approval from appropriate authorities.

— A mass properties uncertainty analysis shall be documented and referenced in the test procedure. Periodically check program requirements and uncertainty-related information and update test requirements as necessary. Uncertainties must be included in the error budget to decide the Accept/Reject criteria.

— The Accept/Reject criteria must be clearly specified in the test mass properties procedure. Any deviation from the criteria must be approved by the proper authorities in writing before proceeding with the test.

5.3.4.4 Test Configuration

The mass properties test configuration shall be documented such that personnel can clearly understand that the test item is ready before starting the test. Any change during the test shall be recorded and evaluated to validate that the test objectives and requirements are met. Any configuration change after the test shall be monitored and assessed for impact on requirements to assure the mission success. The following requirements shall be addressed.

— The test article shall simulate the flight condition to the extent practical, excluding hazardous components or components not normally installed at the measurement site. Deviations from the flight condition should be commensurate with test objectives such that the test results are meaningful and measurement uncertainties within expected ranges.

— Configuration Verification: The cognizant manager or authorized designee, vehicle engineer, and responsible quality control engineer shall verify the test article configuration, provide a list of shortages (all missing flight items) and overages (non-flight items installed) and tare items, and sign and certify that the test configuration meets above test configuration requirements.

— The mass properties test director (Mass Properties Lead Engineer, or designee) shall review the certificate and sign acceptance before starting the mass properties test.

— The use of mass simulators instead of flight items in any test shall be accurately documented.

— The mass properties test director shall perform a simulation and compensation analysis for the shortages and overages, and prepare and install the simulation and compensation weights during the appropriate test process.

— The mass properties test director or authorized designee shall verify the GSE used in each mass properties testing step to assure that the GSE has a valid proof load certificate.

— Illustration of the coordinate system shall be provided in the TP to describe the coordinate systems used for the test article, GSE, and test equipment; and provide a table to identify the relationship

DRAFT

between the different coordinate systems if the test item coordinate system is different from that of the test equipment or GSE.

5.3.4.5 Test Sequence

The test procedure shall include a detailed step-by-step sequence to be followed. All changes from the sequence must be authorized by the responsible MPE test director. The MPE test director and the responsible quality assurance (QA) engineer shall mark the changes in red, initial the changes, and record the changes in a Variance Discrepancy Log (VDL). MPE and QA shall initial each test step prior to proceeding to the next. Data shall be provided for each measurement. MPE and QA shall sign and date all test data sheets.

A general test sequence is described in the following example.

- Test set-up—describe the step-by-step set-up procedure for the test equipment or follow the sequence from the released SWI. The SWI shall be referred and attached in the test procedure during the test. Test site cleanliness practices commensurate with the requirements shall be followed.
- Install and secure the GSE per TP
- Align the GSE per approved alignment procedure or SWI. Record alignment raw data for each iteration until the alignment requirements are met. MPE shall verify the alignment accuracy and analyze the effect of the residual alignment error on the test results to assure that the overall alignment is acceptable.
- Perform tare balance or mass properties measurements (for example, MOI) per TP
- Verify test item test configuration. Sign acceptance if the test configuration requirements are met
- Weigh test item per TP or SWI before the installation on GSE and then perform test item alignment
- Install simulation and compensation mass per analysis for the shortages and overages.
- Perform test item balance or other mass properties measurements. Install balance mass as required per TP until the requirements are met. Take inventory of the balance mass and record in the data sheet.
- Perform data reduction
- Compare the test results with the predicted results. Summarize results with comparisons to the predicted or expected results and make timely assessment.
- Remove the test item from GSE and take final mass measurement
- Proceed with load cell calibration per TP or SWI
- Publish “As-Measured” Mass Properties Report

5.4 Database Management

5.4.1 Scope

The contractor shall establish a mass properties data management system to assure accuracies of the space system mass properties models and support the program reporting requirements. The contractor’s space system mass properties database shall be maintained current by periodic updating to reflect the most recent information from design data, drawings, mass properties measurements, CFE data, associate contractors, subcontractors, and vendors.

DRAFT

5.4.2 Data Management System

The contractor shall employ a data management system that provides accurate representation of the space system mass properties throughout the mission and supports the mass properties reporting requirements for the program. The contractor may utilize an internally developed database management tool or an acceptable vendor-supplied database management tool that meets the minimum requirements as specified in the following sections.

5.4.2.1 Minimum Database Requirements

The contractor's mass properties database management tool shall be capable of providing the following features.

- Standard mass properties calculations from parts, assemblies, installations to space system, payload, and space system levels.
- Mass properties database formatting flexibility (Functional Subsystem and Work Breakdown Structure data organization and sort capability).
- Propellant modeling capability
- Import (e.g., from computer-aided design databases) and export (e.g., to Excel spreadsheet formats) capabilities.
- Mass change, mass maturity, and material usage information.
- User definable fields and custom report formats.
- Unit system of measure conversion flexibility (English or Metric units).

5.4.2.2 Frequency of Database Update

The database shall be updated on a regular schedule to be current with the space system design activity and meet the overall program requirements for reporting. A recommended guideline for the frequency of database update is provided in paragraph E.2.1.1 of Annex E.

5.4.3 Data Organization Utility

The mass properties database shall have the flexibility to sort and report mass properties data in multiple formats as described in the following sections.

5.4.3.1 Functional Subsystem Organization

To provide a uniform basis for mass properties comparisons, the space system mass properties shall be categorized on a functional basis. For example, the mass of all items that function primarily as the space system structure shall be accumulated for the total mass of the space system structure. Annex C provides a discussion of the need for a functional breakdown and guidelines for the functional categorization of component mass. In order to achieve functional mass breakdown consistency, the contractor shall use the guidelines in Annex C.

5.4.3.2 Sectional Organization

When the space system comprises sections for which knowledge of the section mass properties is required, the mass properties data for the sections shall be developed separately. Examples of this include a propulsive vehicle stage having more than one stage, an independently movable section of a space system, and FEM mass distribution modeling. The functional organization shall be maintained within the mass properties data of each section.

DRAFT

5.4.3.3 Work Breakdown Structure (WBS) Organization

The database shall have the organization and sort capability to show correlation to the program contract Work Breakdown Structure. This typically means a correlation of component masses to their respective drawing numbers. This shall be done at a level of detail that permits the determination that the masses of all items on the space system have been included properly.

5.4.3.4 Customer-Furnished Equipment

The contractor's mass properties records shall have a separate tabulation of all CFE.

5.4.4 Database Record Keeping

The contractor shall maintain records of the detailed mass properties database in electronic format. The databases at ATP, PDR, CDR, PSRR, and launch, as a minimum, shall be retained for the duration of the program.

5.5 Documentation

5.5.1 Documentation Requirements

The required documents specified by this standard include, but are not limited to, those described in the following sections. The document submittal requirements are specified in 5.5.2 and Annex E.

5.5.1.1 Mass Properties Control Plan

A Mass Properties Control Plan in accordance with 5.1 shall be developed and documented by the contractor. The plan shall state the management program and procedures to be used for mass properties control, verification, and documentation during the various procurement phases.

5.5.1.2 Verification Plan

A mass properties verification plan, in accordance with 5.3, that describes and substantiates the methods to be used to verify the program critical mass properties parameters shall be developed and documented by the contractor.

5.5.1.3 Mass Properties Test Procedures

Each mass properties measurement must be performed in accordance with approved and released test procedures, or approved and documented detailed work/process instructions. Measurement of critical mass properties at the space system level require detailed instructions specified in a formal test procedure. Measurement of the mass of a unit, part, or an assembly using a load cell or platform scale may be performed with approved detail work/process instructions. The required content for mass properties test procedures is specified in 5.3.4.

5.5.1.4 Test Completion Reports

The records for each critical mass properties test, performed in accordance with approved and released procedures, shall be documented in a test completion report. As a minimum, the report shall include the following.

— A concise summary of the measurement results and predicted compliance against the requirements. In cases where non-compliance is predicted, quantify the impact to space system performance and state the plan to resolve the problem.

— Summarize the critical mass properties and their limits for which the validation measurements were executed.

DRAFT

- Include the results of uncertainty analyses that provide a worst-case bound on the measurement results to properly predict whether requirements are met with adequate margin.
- Prepare documentation that demonstrates that all the steps in the test procedure were performed and that the recorded measurement data is correct.
- Prepare copies of all the raw test data measurements taken, with clear annotation on the data records to indicate the date and time (in chronological sequence) when the test data was taken.
- Include applicable diagrams and coordinate system definitions to indicate the spatial relationship between the test data, test equipment, and the flight test article.

5.5.1.5 Contract Change Proposals

Information necessary to evaluate and substantiate the effect on vehicle mass properties resulting from proposed changes shall be submitted with the change proposal..

5.5.1.6 Mass Properties Status Report

A Mass Properties Status Report that includes the elements described in the following subsections shall be developed and documented by the contractor.

5.5.2 Document Elements

Documents shall be composed of those applicable elements listed in Table E.1 and E.2 of Annex E. The description of the elements is specified in 5.5.3.

5.5.3 Document Element Description

5.5.3.1 Title Page

A title page should contain the following information, as applicable:

- Document number
- Type of submittal
- Vehicle flight number
- Step, stage or module
- Applicable serial numbers
- Date of issuance
- Actual date of data reported
- Contractor's name
- Mission identification

5.5.3.2 Table of Contents

A Table of Contents is a listing of the document elements and their location within the report.

5.5.3.3 Introduction

Define the scope or purpose of the document and concisely summarize the significant material presented in the document.

DRAFT

5.5.3.4 Mass Properties Summary

The mass properties summary shall include the following.

a) Mass Status—Current basic and predicted mass, change to basic and predicted mass from last status, not-to-exceed mass allocation (specification) and margin against requirement for the following:

   1) Spacecraft (Bus) functional subsystems

   2) Payload subsystems

   3) CFE

   4) Space system dry mass

   5) Propellants and pressurant

   6) Space system wet mass

   7) Launch vehicle adapters and mission peculiar items

   8) Space system launch mass

   9) Launch Vehicle capability

b) Design Maturity Status—show percentage of mass categorized by maturity code (as defined in Table 1) for the following configurations:

   1) Spacecraft (Bus) functional subsystems

   2) Payload subsystems

   3) Space system (dry)

c) Mass Properties Requirements (Limit monitoring)—present a tabulation of all the critical mass properties parameters and provide the following for each requirement to substantiate the predicted performance against the requirement:

   1) Description of the parameter

   2) Current basic (nominal) parameter value

   3) Uncertainty

   4) Current predicted parameter value (sum of basic + MGA + uncertainty)

   5) Specification requirement or derived limit

   6) Predicted compliance to the requirement (margin)

   7) Indicate method to verify the requirement (analysis or test)

   8) List the source of the requirement

d) Mass Properties Summary—provide a tabulation of the current space system stowed configuration mass properties (mass, center of mass, moment of inertia, product of inertia) in an orderly build-up from the dry space system to the space system configuration at separation from the launch vehicle. Provide the mass properties data for the following conditions, as a minimum:

   1) Spacecraft (Bus) functional subsystems

   2) Payload functional subsystems

DRAFT

3) CFE

4) Space system dry

5) Propellants and Pressurant

6) Space system at separation from the launch vehicle

e) Technical Performance Measurement charts—provide TPM charts for all critical mass properties requirements as typified in Figure 3, Subsection 5.1.3.4.2.

Summarize concerns and new technical issues that impact the space system mass properties.

5.5.3.5 Mass Change Analysis

Prepare a detailed tabulation of the space system mass changes that have occurred since the last status report. The changes shall be grouped by functional subsystems for the Spacecraft (Bus) and Payload. Provide the following information, as a minimum, for each mass change.

— Date of incorporation into the database

— Database functional code

— Mass change code (as defined in Table 3)

— Description of the change

— Current basic mass of the item(s) changed

— Incremental mass change for the item(s) Basic mass, Growth mass, and Predicted mass

5.5.3.6 Mass Change Summary by Change Code

Prepare a tabulated summary, at the space system level, of the total mass change coded to each change category (as defined in Table 3) for each status report, and show a running total of the mass change total by change category from program ATP.

5.5.3.7 Pending and Potential Changes

All pending or potential design changes with threats to increase and opportunities to decrease the system mass shall be documented. The changes shall be grouped by functional subsystem. Each potential change shall be evaluated and assigned a percent probability of occurrence as specified in subsection 5.1.3.2.5. A closure date shall be assigned to each item to indicate when disposition to drop or implement the change will be made. An evaluation of impacts for each potential change shall be made and documented. Prepare the following information, as a minimum, for each identified change.

— Description of the change

— Functional subsystem(s) affected

— Estimated item(s) Basic mass, Growth mass, and Predicted mass

— Probability of Occurrence: High, Medium High, Medium Low, or Low

— Closure date

5.5.3.8 Reference Coordinate Axes and Space System Configurations

5.5.3.8.1 Coordinate Axes

A diagram shall be prepared that relates the location and orientation of the reference axis system used for mass properties determination to the space system. The exact location of the reference axis system origin with respect to the vehicle should be noted on the diagram. If the space system comprises more than one section, and each section has a different reference axis system, each system should be similarly described. Their mutual relative locations and orientations should also be described.

Guidelines for reporting the mass properties of flight vehicles have been developed by the Society of Allied Weight Engineers (SAWE) in recommended practice number 6. It is recommended that these guidelines be utilized when developing a reference axis system.

5.5.3.8.2 Space System Configurations

Include CAD model depictions of the Space System in the stowed and deployed configurations with the coordinate axes attached for reference.

5.5.3.9 Sequenced Mass Properties

Prepare data (mission event, mass, center of mass, moments of inertia, and products of inertia) for the space system at each significant mission event from launch (showing the dry and wet conditions) through the end of the mission. The mission events shall be presented according to the mission timeline, showing the space system mass properties for pre- and post-propellant burns and deployments.

5.5.3.10 Space system Movable Objects

Prepare tabulated mass properties data for all of the space system elements that move during the mission sequence from launch to end of mission (e.g., antennas, solar array, payload sensors). The information shall include the following for each movable object at a minimum.

- Pivot point or translation point location in the space system coordinate axes
- Stowed mass properties
- Deployed mass properties (nominal deployed position)

5.5.3.11 Mission-Critical Mass Properties

Include tabulations of the significant mass properties parameters that vary during the mission sequence and are used to derive mission performance (e.g., attitude determination, stability, and control). Examples include, but are not limited to, the following:

- tabulation or plot of mass, center of mass, pitch, yaw and roll moments of inertia versus mission time,
- tabulation or plot of spin-to-transverse inertia ratio, spin-axis tilt (wobble angle) and phase angle versus mission time.

5.5.3.12 Uncertainties

The requirements for mass properties uncertainty determination are generally specified in 5.1.3.2.4 and 5.2.5.1. Mass property parameter uncertainties must be considered when evaluating the following:

- assessment of mass properties predicted performance and compliance to requirements,
- selection of mass properties verification methods, either test or analysis,
- selection of test equipment accuracy/sensitivity.

5.5.3.13 PLACEHOLDER (Fluid and Propellant Loads info deleted)

5.5.3.14 Mass Distribution

Mass distribution models, to support the analysis tasks of engineering technical specialties such as Stress/Dynamics and Ground Systems, should be documented and correlated to defined mass properties models. Mass distribution models support the development of:

— Finite-Element Models

— Ground support equipment designs (lifting slings, handling fixtures, etc.)

5.5.3.15 Mass Growth Allowance and Depletion Schedule

The Mass Growth Allowance (MGA) depletion schedule agreed to in the Mass Properties Control Plan shall be used for reporting.

5.5.3.16 Space System Design Features

These data include major dimensional factors, design criteria, and design features used in the development of the reported mass properties. Annex C presents a list that may be used as a guide for data submitted.

5.5.3.17 Detailed Mass

Prepare a tabulation of the current space system detailed mass properties by functional subsystem or drawing tree structure. Show the following for each line of detail.

— Functional code

— Description

— Basic mass

— Predicted mass

— Percent of basic mass in each category as coded in Table 1)

— Mass Growth Allowance (MGA)

5.5.3.18 Detailed Mass Properties

Prepare a tabulation of the current space system detailed mass properties by functional subsystem or drawing tree structure. Show the following for each line of detail.

— Functional code

— Description

— Basic mass

— Predicted mass

— Center of Mass (X, Y, Z)

— Moment of Inertia (Ixx, Iyy, Izz)

— Product of Inertia (Ixy, Ixz, Iyz)

5.5.3.19 Definitions and Acronyms

Include a list of definitions and acronyms specific to the document.

5.5.3.20 References

All documents shall include a listing of the pertinent references, such as data sources, reports correspondence, substantiating documents, and any other material germane to the document.

DRAFT

5.5.3.21 Evaluation of Flight

Compare the actual launch mass properties and the actual mass properties variations observed throughout the flight with the predicted mass properties flight data. An evaluation of the critical mass properties, uncertainties, and other pertinent data shall be included in any final post-flight report to substantiate the contractor's predicted mass properties and confirm either expected flight mass properties conditions or apparent anomalies.

DRAFT

Annex A Supplemental Information for Terms and Definitions (Informative)

A.1 Mathematical Descriptions

The following mathematical descriptions are provided to aid understanding of certain definitions contained in Section 4.2.

A.1.1 Mass

Unlike weight, mass is an intrinsic property that is independent of the gravitational field. Mass is given by $m = \int dm$ for a continuous system or $m = \sum m_i$ for a discrete system.

A.1.2 Center of Mass

The center of mass in the X-axis is given by $X_{cm} = \frac{(\int xdm)}{m}$ for a continuous system or $x_{cm} = \frac{(\sum m_i x_i)}{m}$ for a discrete system relative to a defined, fixed coordinate system.

A.1.3 Moment of Inertia

Moments and products of inertia together quantify the distribution of mass relative to a defined coordinate system. Moments of inertia are defined as the sum of the products of each element of mass by the square of the perpendicular distance from a specified axis. For example, the moment of inertia about the X-axis is given by $I_{xx} = \int (y^2 + z^2) dm$ for a continuous system or $I_{xx} = \sum m_i (y_i^2 + z_i^2)$ for a discrete system. Typically, moments of inertia are defined with respect to the center of mass.

A.1.4 Product of Inertia

Products of inertia are defined as the sum of the product of each element of mass by the perpendicular distances from two specified axes. For example, a positive integral product of inertia about the X and Y-axes is given by $I_{xy} = \int xydm$ for a continuous system or $I_{xy} = \sum m_i x_i y_i$ for a discrete system. Usually, products of inertia are defined with respect to the center of mass.

Products of inertia are often defined as the negative integral $(I_{xy} = -\int xydm)$. Special attention should be paid to understanding whether a positive or negative integral is used in the determination of the products of inertia. POI is expressed in the same units as MOI, but it can have either positive or negative polarity.

The combination of moments and products of inertia, presented as an inertia matrix in the coordinate system of interest, quantify the effects of the distribution of mass upon the rotational dynamics of a body. There are three principal axes for any rigid body. A body will spin without dynamic imbalance about any of its three principal axes. The dynamic imbalance of a body spinning about any one of its principal axes is zero. A body will spin naturally without constraints about the principal axis with the largest moment of inertia. The values of the products of inertia of a body are zero if the axes of the coordinate system used to describe the body's inertia are aligned with the body's principal axes.

DRAFT

A.2 Vehicle Specific Mass Definitions

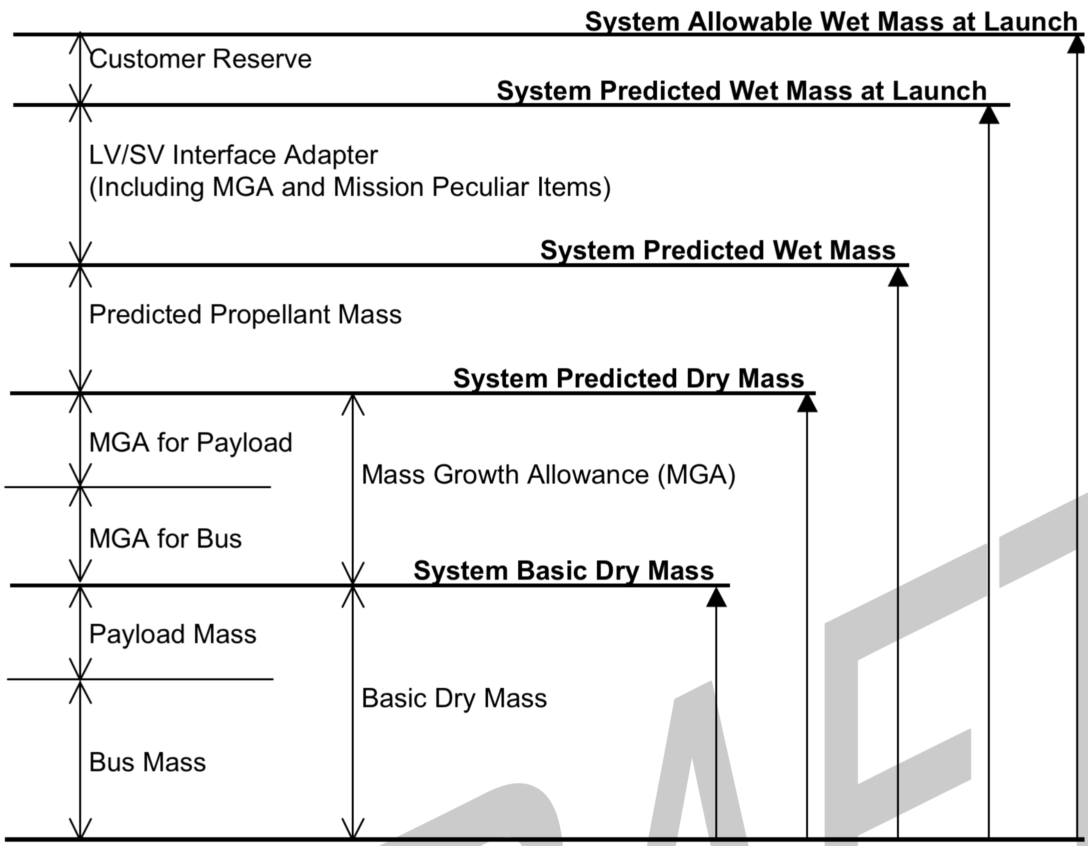


Figure A.1 — Space vehicle mass definitions

DRAFT

Annex B Placeholder heading (info moved to Section 5.2.4.3)

DRAFT

Annex C Functional Breakdown of Mass (Informative)

C.1 Scope

Space systems are comprised of subsystems that perform specific functions. Examples of two subsystems are structural support for equipment and electrical power. Useful subsystem information is generated when component masses are accumulated on a functional basis. The uses of functional subsystem mass include the tracking of functional mass during design for mass proposed for new vehicles, and the improvement of the database used for the refinement of mass-estimating methods. It is necessary to strive for consistency regarding which components comprise each subsystem if the objectives of subsystem mass estimation and evaluation are to be achieved. Consideration should also be given to the configuration for which actual mass data will be obtained. The following sections provide guidelines for achieving this consistency.

C.2 Referenced Documents

JSC-23303 (March 1989)	Design Mass Properties, Guidelines and Formats for Aerospace systems (NASA Johnson Space Center).

C.3 Approach

C.3.1 Establishment of a Subsystem List

In accordance with Section B.1, wherein the functional basis is discussed, a list should be established that names each of the subsystems comprising the space system. Since the term "space system" is representative of a large variety of vehicles with a wide range of complexities, specifying a comprehensive subsystem list in this Appendix is not considered advisable. However, multiple example subsystem lists are given in Tables C.1 through C.4, which are intended to serve as guides. Additional guidelines can be found in JSC 23303. The contractor should develop a subsystem list suitable for the space system being developed. This contractor's list should contain subsystems in at least as much detail as represented in Tables C.1 through C.4.

C.3.2 Subsystem Breakdown

C.3.2.1 Second Level of Detail

Each subsystem total mass should be broken down to a second level of detail. This second level of detail should be constructed to provide useful information for mass estimation and evaluation. For example, useful information is provided when a satellite electrical power subsystem is broken down into components of solar array, batteries, and power conditioning. Representative subsystem breakdowns to a second level of detail are shown in Tables C.1 through C.4. The contractor should establish the applicable second-level mass breakdown and it should be at least to the level of detail represented in Tables C.1 through C.4.

C.3.2.2 Subsequent Levels of Detail

A breakdown of the second level of detail to a third level may be useful. Examples of this are shown in Tables C.1 through C.4. As in the case of the second level of detail, the third level may be needed for mass evaluation and estimation. The Contract Data Requirements List (CDRL), incorporated into the contract, may require the contractor's subsystem list, the second-level-of-detail list, and any subsequent level-of-detail lists, be prepared for review and approval by the procuring authority.

C.3.3 Functional Coding

The contractor should develop a functional code that is consistent with the subsystem list and level of detail lists described in Sections C.3.1 and C.3.2. The code format is not specified. As masses are determined, they should be coded and accumulated by the codes.

DRAFT

C.3.3.1 Ambiguities

In the process of coding items to a function, ambiguities are likely to occur. For example, a solid propellant motor case may have two functions: propulsion and basic structure. A cylindrical portion of a motor case may be partially designed by the loads produced by the payload the launch vehicle carries and partially designed by the case internal pressure. The domes are designed by the internal pressure and the motor case skirts are designed by axial and bending loads. Another example would be the structure used to support the solar cells on a deployable solar array panel. Arguments can be made for either a structure or electrical power functional code.

C.3.3.2 Resolution of Ambiguities

For those items that have more than one function, the contractor should code them to the primary function. Refer to Table C.5 for guidance. If the choice is not obvious, the contractor may make an arbitrary decision. When arbitrary decisions are made for items constituting at least 10% of the subsystem mass, the contractor should maintain descriptive titles in the mass properties records of the space system. This permits the transfer of these items from one function to another at the discretion of the procuring authority.

DRAFT

Table C.1 — Sample Functional Breakdown (Satellite)

1. Payload
2. Structure
    - 2.1 Basic Structure
        - 2.1.1 Main Truss
        - 2.1.2 Equipment, Bulkheads, and Platforms
        - 2.1.3 Kick Motor Support Cone
    - 2.2 Secondary Structure
        - 2.2.1 RCS Tank Supports
        - 2.2.2 Momentum Wheel Supports
        - 2.2.3 Solar Array Retention Fittings
    - 2.3 Adapter, Separation
    - 2.4 Mechanical Integration (hardware, clips, misc.)
3. Thermal Control
    - 3.1 Louvers
    - 3.2 Heat Pipes
    - 3.3 Insulation
    - 3.4 Surface Mirrors, Paint
4. Electrical Power
    - 4.1 Solar Array
        - 4.1.1 Power Source
        - 4.1.2 Substrate
        - 4.1.3 Drives
    - 4.2 Converters
    - 4.3 Power Switches
    - 4.4 Electrical Integration (harness, connectors, hardware, misc.)
5. Guidance, Navigation
6. Data Management
7. Telemetry, Tracking, Command
8. Orientation Control
9. Reaction Control
10. Propulsion
11. Mass growth allowance
12. Fluids

DRAFT

Table C.2 — Sample Functional Breakdown (Liquid Propulsion Stage)

1. Structure
    - 1.1 Fuel Tank
        - 1.1.1 Domes
        - 1.1.2 Cylinder
        - 1.1.3 Skirts
        - 1.1.4 Anti-slosh Devices
    - 1.2 Oxidizer Tank
    - 1.3 Intertank Structure
    - 1.4 Thrust Structure
    - 1.5 Launch Supports
2. Thermal Control
3. Main Propulsion
    - 3.1 Rocket Engine
        - 3.1.1 Thrust Chambers
        - 3.1.2 Pumps
        - 3.1.3 Engine Systems
    - 3.2 Fuel Feed
    - 3.3 Oxidizer Feed
    - 3.4 Pressurization
    - 3.5 Fill, Drain, Vent
4. Thrust Vector Control
5. Reaction Control System
6. Secondary Power
    - 6.1 Electrical
    - 6.2 Hydraulic
7. Avionics
    - 7.1 Guidance, Navigation and Control
    - 7.2 Data Management
    - 7.3 Telemetry, Tracking and Command
    - 7.4 Command and Data Handling
8. Range Safeties and Abort
9. Mass Growth Allowance

DRAFT

10. Fluids

10.1 Impulse Propellant

10.2 Residual Propellant

10.3 Reserve Propellant

10.4 Bias Propellant

10.5 Outage Propellant

10.6 Pressurization Gas

DRAFT

Table C.3 — Sample Functional Breakdown (Non-Man Rated Launch/Ballistic Vehicles)

1. Stage I
    - 1.1 Oxidizer tank
    - 1.2 Intertank
    - 1.3 Fuel Tank
    - 1.4 Engine Section
    - 1.5 Propulsion
    - 1.6 Interstage
        - 1.6.1 Primary Structure
            - 1.6.1.1 Forward Rings
            - 1.6.1.2 Aft Rings
            - 1.6.1.3 Skin
            - 1.6.1.4 Doors
            - 1.6.1.5 Fasteners
            - 1.6.1.6 Actual Weight Adjustment
        - 1.6.2 Secondary Structure
        - 1.6.3 Environmental Protection
        - 1.6.4 Separation Systems
        - 1.6.5 Electrical/Electronics System
        - 1.6.6 Actual Weight Adjustment
2. Assist Motors
3. Stage II
4. Stage III
5. Payload Attach Fitting
6. Payload Fairing
7. Payload

DRAFT

Table C.4 — Sample Functional Breakdown (Manned Reentry Vehicle)

1. Crew and Flight Crew Equipment
2. Environmental Control and Life Support Systems (ECLSS)
3. Structure
    - 3.1 Primary Structure
    - 3.2 Secondary Structure
    - 3.3 Ingress/Egress Hatch
    - 3.4 Service Module Adapter, Separation System
4. Thermal Control
    - 4.1 Active Cooling
    - 4.2 Insulation
    - 4.3 Surface Mirrors, Paint
5. Thermal Protection System (for reentry)
6. Electrical Power
    - 6.1 Batteries
    - 6.2 Converters
    - 6.3 Power Switches
    - 6.4 Electrical Integration (harness, connectors, hardware, misc.)
7. Avionics
    - 7.1 Guidance, Navigation & Control
    - 7.2. Data Management
    - 7.3. Telemetry, Tracking, Command
    - 7.4. Command and Data Handling
8. Recovery Systems
9. Seats
10. Landing Attenuation
11. Reaction Control System
12. Orbital Maneuvering Propulsion System

12\. Expendable Fluids

DRAFT

Table C.5 — Category Descriptions

Table 1 Hardware Categories	Description
Electrical/ Electronic Components	— Primary purpose is to manage electronic data or power — Any unit requiring electrical power except as reserved for other categories such as Battery, Solar Array, Thermal Control, Mechanisms, Propulsion or Instrumentation — Includes but is not limited to: a chassis that houses the electronic components. This includes but is not limited to: communications, avionics, computers, and power conditioning, conversion or distribution
Structure	— Primary purpose is to provide structural support for primary and secondary loads, and attachments — Includes but is not limited to: support panels, support tubes or trusses, doublers*, and adapters
Brackets, Clips, Hardware	— Primary purpose is to provide support for bracketry, attach hardware, grounding tabs, support or clamps for cables, wiring, and propellant lines
Battery	— Primary purpose is to provide stored electrical power — Includes but is not limited to various sorts of power cells — Units that support Power Conditioning should be under Electrical/Electronic Components
Solar Array	— Electrical device consisting of a collection (array) of connected solar (photovoltaic) cells used for converting solar energy into electricity
Thermal Control	— Primary purpose is to manage or control the temperature of the system — Includes but is not limited to: various louvers, heat pipes, blanketing, mirrors, thermal protection systems, thermal surface finishes, heaters, radiators, and phase changing materials
Mechanisms	— Primary purpose is to provide mechanical linkage for the reorientation or repositioning of other devices, also, mechanical devices that move — Includes but is not limited to: various deployment mechanisms, positioners, gimbals, bearing assemblies, and momentum or reaction wheels
Propulsion	— Primary purpose is to provide axial or lateral thrust and/or attitude control to the system — Includes but is not limited to: propellant tanks (liquid and/or gas), thrusters (examples are chemical-liquid, chemical-solid; electric, nuclear), valves, manifolds, feed lines and fittings
Wire Harness	— Primary purpose is to transmit signals or power to the rest of the system — Includes but is not limited to: flat or round conductive wiring, fiber optic lines, coax cabling, ordnance transfer lines
Instrumentation	— Primary purpose is to sense or measure the operating environment — Includes but is not limited to: thermocouples, strain gages, vibration transducers, accelerometers
ECLSS, Crew Systems	— Primary purpose is to provide a habitable environment for a flight crew in a crew compartment of a manned space system in addition to cooling or heating various space systems or components — Typically consists of an air revitalization system, water coolant loop systems, atmosphere revitalization pressure control system, active thermal control system, supply water and waste water system, waste collection system and airlock support system
Solid Rocket Motor Inerts	— Primary purpose is to provide thrust from solid propellant. Typically, this is in the form of rocket motors but can include gas generators that use solid propellants to create hot gases for other uses. — Includes but is not limited to: motor cases, liner, internal insulation, and nozzles

NOTE These category definitions are for the purpose of assigning a mass growth allowance and not intended to be used as subsystem definitions for a specific program

*Doublers could be either categorized under Structure or Thermal Control; suggest categorizing by primary usage. See ambiguities in Annex C.

DRAFT

Annex D Space System Design Features (Informative)

D.1 Scope

This Annex is a guide for reporting design parameters that have major influences on space system subsystem mass.

D.2 Referenced Documents

(Not Applicable).

D.3 Major Reporting Parameters

The following categories of data are useful for evaluating subsystem mass during the early design phase and for the improvement of mass estimating techniques.

D.3.1 Unmanned Satellite

a) Vehicle sketch giving major dimensions

b) Design Life

c) Electrical power subsystem description (solar array, battery)

- Solar array area, cell thickness, cover glass thickness, substrate type, and materials
- Battery type, depth of discharge, capacity, number of battery cells
- Bus voltage

d) Attitude Control

- Type (momentum, magnetic, mass expulsion, etc.)
- Pointing accuracy, slew angles, and rates

e) Propulsion Subsystem—for maneuvering or orbit changes

- Propellant Type
- Pressurization Method
- Number of tanks and tank size
- Number of thrusters and thrust rating
- Total Velocity Increment

f) Thermal Control

- Type (paint, insulation, louvers, heat pipes, refrigerators)
- Radiator Area

g) Structure

- Material Type(s)
- Construction Type(s) (Monocoque, Skin/Stringer, etc.)

DRAFT

D.3.2 Liquid-Propellant Stage

a) Vehicle sketch giving major dimensions, tank geometry, etc.

b) Structural materials and types

c) Tank design pressures

d) Safety factor

e) Structural design conditions, loads

f) Engine data

- Thrust, Specific Impulse (Sea Level and Vacuum)
- Expansion Ratio
- Chamber Pressure
- Throttling Ratio
- Number of Engines
- Number of Starts
- Throat Area

g) Propellant type, mixture ratio by volume or mass, densities

D.3.3 Solid-Propellant Stage

a) Vehicle sketch giving major dimensions

b) Chamber pressure—average and maximum expected

c) Safety factor

d) Case structural material, number of segment joints

e) Burn time

f) Nozzle materials, throat area, expansion ratio(s)

g) Thrust vector control type

h) Propellant density, loading fraction

i) Specific impulse—sea level, vacuum

D.3.4 Reentry Vehicle

a) Vehicle sketch giving major dimensions

b) Lift-to-drag ratio

c) Thermal protection system type

d) Wetted area (total)

e) Pressurized volume

f) Mission duration

DRAFT

g) Structural materials and types

h) Wing span, root chord length and thickness, plan area (define)

i) Safety factor

j) Ultimate load factor and associated mass

k) Stabilizing and control surface areas

l) Landing system type (parachute, retro-rockets, etc.)

m) Propellant type, mixture ratio, densities

n) Reaction control system type, propellant type

o) Auxiliary propulsion system type, propellant type

p) Crew size

DRAFT

Annex E Document Content and Submittal Schedule (Normative)

E.1 Schedule of Submittals

The schedule for the required documents specified by this standard shall be specified in the Contract Data Requirements List (CDRL) for each deliverable specified by a Data Item Description (DID). As an example, a typical mass properties document content and submittal schedule is presented in Table E.1 and Table E.2 of Annex E.

E.2 Distribution

The contractor is responsible for the distribution of these documents to the appropriate members of the space system team and shall include distribution to the organizations specified by the procuring activity.

DRAFT

Table E.1 — Example Document Content and Submittal Schedule

	PROGRAM PHASE	1	2	3	4	5	6	7	8	9
		PRE-SYSTEMS ACQUISTION			SYSTEMS ACQUISTION					
		PRE-KDP-A	PHASE A		PHASE B					
		CONCEPT STUDIES	CONCEPT DEVELOPMENT		PRELIMINARY DESIGN					
	Column No.	1	2	3	4	5	6	7	8	9
	SCHEDULE OF SUBMITTALS	Monthly for studies < 2 months; At first of each month for studies > 2months; Semiannually for studies > 1 year or more; At completion of all studies;	Monthly for studies < 2 months; At first of eache month for studies > 2 months; Semiannually for studies > 1 year; At completion of all studies; At major design reviews;	With submittal of all proposals	At Authorization To Proceed (within 30 days of)	Monthly Reports - at first of each month between ATP and PDR	At PDR	Mass Properties Control Plan - within 60 days after ATP	Verification Plan - submittal with PDR package	Contract Change Proposal - with each contract change proposal
	DOCUMENT TYPES	Status Report	Status Report		Status Report			Procedural		Misc.
Section	DOCUMENT ELEMENT									
5.5.3.1	Title Page	x	x	x	x	x	x	x	x	x
5.5.3.2	Table of Contents	x	x	x	x	x	x	x	x	x
5.5.3.3	Introduction	x	x	x	x	x	x	x	x	x
5.5.3.4	Mass Properties Summary	x	x	x	x	x	x			
5.5.3.5	Mass Change Analysis	x	x		x	x	x			
5.5.3.6	Mass Change by Summary Code				x	x	x			
5.5.3.7	Pending and Potential Changes	x	x	x	x	x	x			
5.5.3.8	Coordinate Axes and Space System Configurations	x	x	x	x	x	x			
5.5.3.9	Sequenced Mass Properties			x	x	x	x			
5.5.3.10	Space Systems Movable Objects			x	x	x	x			
5.5.3.11	Mission Critical Mass Properties	x	x	x	x	x	x			
5.5.3.12	Uncertainties			x	x	x	x		x	
5.5.3.13	Fluid and Propellant Loads	x	x	x	x	x	x			
5.5.3.14	Mass Distribution									
5.5.3.15	Mass Growth Allowance & Depletion Schedule	x	x	x	x	x	x	x		
5.5.3.16	Space Vehicle Design Features	x	x	x	x	x	x			
5.5.3.17	Detail Mass	x	x	x	x	x	x			
5.5.3.18	Detailed Mass Properties				x		x			
5.5.3.19	Definitions and Acronyms	x	x	x	x	x	x	x	x	
5.5.3.20	References	x	x	x	x	x	x	x	x	
5.5.1.1	Mass Properties Control Plan							x		
5.5.1.2	Verification Plan								x	
5.5.1.3	Test Procedure									
5.5.1.4	Test Completion Report									
5.5.3.21	Actual Data Records									
5.5.3.22	Evaluation of Flight									

DRAFT

Table E.2 — Example Document Content and Submittal Schedule

PROGRAM PHASE		SYSTEMS ACQUISITION									
		PHASE C				PHASE D					
		COMPLETE DESIGN				BUILD & OPERATIONS					
Column No.		10	11	12	13	14	15	16	17	18	19
SCHEDULE OF SUBMITTALS		Monthly Reports - at first of each month between PDR and CDR	AT CDR	Verification Plan Updated - submittal with CDR package	Contract Change Proposal - with each contract change proposal	Quarterly Reports - at first of each quarter between CDR and Launch	Final Mass Properties Testing - 14 days after test	At Pre-Ship Readiness Review	As-launched report within 14 days after launch	Test Procedures - 60 days in advance of the scheduled test	Test Completion Report - within 30 days after completion of test
DOCUMENT TYPES		Status Report		Procedural	Misc.	Status Report				Miscellaneous	
Section	DOCUMENT ELEMENT										
5.5.3.1	Title Page	x	x	x	x	x	x	x	x	x	x
5.5.3.2	Table of Contents	x	x	x	x	x	x	x	x	x	x
5.5.3.3	Introduction	x	x	x	x	x	x	x	x	x	x
5.5.3.4	Mass Properties Summary	x	x			x	x	x	x		
5.5.3.5	Mass Change Analysis	x	x			x	x	x	x		
5.5.3.6	Mass Change by Summary Code	x	x			x	x	x	x		
5.5.3.7	Pending and Potential Changes	x	x			x	x	x	x		
5.5.3.8	Coordinate Axes and SV Configurations	x	x	x		x	x	x	x	x	x
5.5.3.9	Sequenced Mass Properties	x	x			x	x	x	x		
5.5.3.10	Space Vehicle Movable Objects	x	x			x	x	x	x		
5.5.3.11	Mission Critical Mass Properties	x	x			x	x	x	x	x	
5.5.3.12	Uncertainties	x	x	x	x	x	x	x	x	x	x
5.5.3.13	Fluid and Propellant Loads	x	x			x	x	x	x		
5.5.3.14	Mass Distribution										
5.5.3.15	Mass Growth Allowance & Depletion Schedule	x	x			x	x	x	x		
5.5.3.16	Space Vehicle Design Features	x	x			x	x	x	x		
5.5.3.17	Detail Mass	x	x			x	x	x	x		
5.5.3.18	Detailed Mass Properties		x			x		x	x		
5.5.3.19	Definitions and Acronyms	x	x	x		x	x	x	x	x	x
5.5.3.20	References	x	x	x		x	x	x	x	x	x
5.5.1.1	Mass Properties Control Plan										
5.5.1.2	Verification Plan			x							
5.5.1.3	Test Procedure									x	
5.5.1.4	Test Completion Report						x				
5.5.3.21	Actual Data Records						x				x
5.5.3.22	Evaluation of Flight										

DRAFT

Bibliography

[1] ANSI/AIAA R-020A: American National Standard, Recommended Practice for Mass Properties Control for Satellites, Missiles, and Launch Vehicles

[2] DoDD 5000.1, and .2: Defense Acquisition Guidebook, Chapter 10.5.2. Technology Maturity and Readiness Assessments

[3] MIL-STD-1811: Military Standard, Mass Properties Control for Space systems, Dated 02 April 1992

[4] MIL-M-38310B: Mass Properties Control Requirements for Missile and Space systems, Dated 01 July 1971

[5] MIL-HDBK-1811: DEPARTMENT OF DEFENSE HANDBOOK, Mass Properties Control for Space systems, Dated 12 August 1998

[6] SAWE RP-6A: Standard Coordinate Systems for Reporting the Mass Properties of Flight Vehicles

[7] SAWE RP-11B: Mass Properties Control for Space systems

DRAFT